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Short communication

Computation of trunk stability in forward perturbations—Effects of preload, perturbation load, initial flexion and abdominal preactivation

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ABSTRACT

Spine stability demand influences active–passive coordination of the trunk response, especially during sudden perturbations. The objective of this study was to look at the role of passive, stationary active and reflexive subsystems on spinal stability. Spine stability was evaluated here during pre- and post-perturbation phases by computing the minimum (i.e., critical) muscle stiffness coefficient required to maintain stability. The effects of pre-perturbation conditions (preloading, initial posture and abdominal antagonistic coactivation) as well as perturbation magnitude were studied. Results revealed that higher preload, initially flexed trunk posture and abdominal pre-activation enhanced pre-perturbation stiffness and stability. In contrast to the preload, however, larger sudden load, initial flexion and abdominal preactivation significantly increased post-perturbation stability margin. As a result, much lower critical muscle stiffness coefficient was required post-perturbation. Compared to the pre-perturbation phase, the trunk stiffness and stability substantially increased post-perturbation demanding thus a much lower critical muscle stiffness coefficient. Overall, these findings highlight the crucial role of the ligamentous spine and muscles (in both passive and active states) in augmenting the trunk stiffness and hence stability during pre- and post-perturbation phases; a role much evident in the presence of initial trunk flexion.

1. Introduction

Spinal instability manifests itself via excessive flexibility causing injuries and pain (Knutsson, 1944; White and Panjabi, 1990). Ligamentous thoracolumbar and lumbar spines devoid of musculature exhibit global instability (i.e., buckling) under compression forces as small as 20 N (Lucas and Bresler, 1960) and 88 N (Crisco, 1989), respectively. Much larger forces of about 5 kN have however been estimated in lifting, fast forward flexion and trunk strength exertion tasks (Bazrgari et al., 2008; El Ouaaid et al., 2013; Fathallah et al., 1999) which underline the crucial role of the musculature and neural activity. Three distinct subsystems contribute to spinal stability (Panjabi, 1992, 2003): (1) ligamentous spine and musculature via their passive contributions; (2) musculature via its feed-forward activity and (3) the neuromuscular system via its feed-back reflexive response. Injury or dysfunction in these subsystems deteriorates stability and increases risk of injury and pain (Reeves et al., 2009).

Muscle stiffness increases at higher activation levels (Brown and McGill, 2005) as the number of cross-bridges increases (Cholewicki and McGill, 1995; Ma and Zahalak, 1985). Larger exertions in paraspinal muscles improve trunk stability under perturbation (Brown and McGill, 2009, 2008; Granata et al., 2004; Krajcarski et al., 1999; Moorhouse and Granata, 2007). Passive trunk stiffness, which is relatively small in the neighborhood of neutral upright posture, substantially increases with forward flexion and compression (Arjmand and Shirazi-Adl, 2006a; McGill et al.,1994; Shirazi-Adl, 2006). This enhances trunk stability under disturbances and lowers the demand for reflexive activity (Granata and Rogers, 2007), although the risk of injury may increase in flexed postures due to the overloading of the spine (Granata and Wilson, 2001). Similarly, antagonistic coactivation increases not only the trunk stiffness and stability margin (Brown and McGill, 2008; Brown et al., 2006; Gardner-Morse and Stokes, 1998; Van Dieen et al., 2003) but also the spinal loads and the risk of injury (Arjmand and Shirazi-Adl, 2006a; Granata and Marras, 2000). Excessive antagonistic coactivity may however deteriorate trunk stability due to resulting large compression forces on the spine (El Ouaaid et al., 2013).

Using in vivo and computational studies, it was found that the perturbation load and pre-perturbation conditions (initial load,

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posture and abdominal coactivation) influence the trunk velocity and acceleration as well as the reflexive response of back muscles and spinal loads (Shahvarpour et al., 2014, 2015). Trunk stability was however not quantified in these analyses. The critical coefficient of muscle stiffness (Bergmark, 1989), q_{cr} as a surrogate measure of the trunk stability, is estimated in the current work using a kinematics-driven model (Bazrgari et al., 2009). Trunk stability is quantified before and after forward perturbation while altering perturbation load magnitude, preload, trunk posture and abdominal preactivation. Pre-perturbation conditions and perturbation load are hypothesized to influence trunk stability.

2. Method

A detailed description of in vivo measurements used in this study is published elsewhere (Shahvarpour et al., 2014). In brief, 12 young male subjects (weight 73.0 ± 3.9 kg and height 177.7 ± 3.0 cm) were semi-seated in a sudden forward perturbation apparatus. With the pelvis fixed, a harness was placed on their trunk at the T8 level. The load was applied anteriorly through a cable connected to the harness in front. A load cell placed between the load and the subject measured the applied load while a potentiometer connected to the harness from the back measured the trunk forward displacement. Six experimental conditions were tested (Table 1).

In our previous kinematics-driven FE model studies (Shahvarpour et al., 2015), a trial was chosen randomly among five for each subject and condition since statistical analyses confirmed no learning effect on trials. The simulation started 256 ms before perturbation and continued 1 s after. With the pelvis fixed, the T12–L5 vertebral rotations at each time instance were estimated using the anterior translation measured from the initial upright trunk position at the T8 and given partitioning among lumbar levels (Bazrgari et al., 2009). Angular velocity profiles along with the perturbation load and distributed gravity forces were input into the FE model. The required moments at each level and time instance were partitioned among associated muscles by minimizing the sum of the cubed muscle stresses at each vertebral level (Arjmand and Shirazi-Adl, 2006b). The FE model (Bazrgari et al., 2008, 2009) consisted of 7 rigid bodies including sacrum, L5–L1 vertebral level and thorax–head–hands segment. Six nonlinear shear-deformable beam elements and dampers represented stiffness and damping properties of the passive tissues (Kasra et al., 1992; Markolf, 1970). Trunk inertial and mass properties were taken from the literature (de Leva, 1996; Pearsall et al., 1996; Zatsiorsky and Seluyanov, 1983).

Forty six local muscles inserted into lumbar levels along with 10 global muscles inserted to the thorax accounted for the trunk musculature. Wrapping of global extensor muscles was simulated with a curved line of action and forces at contact points with vertebrae (Arjmand et al., 2006; Shirazi-Adl, 1989, 2006; Shirazi-Adl and Parnianpour, 2000). Abdominal preactivation of muscles in C6 (see Table 1) simulated pre-perturbation using a nonzero lower constraint (3–5% of maximum active force) that dropped to 1% after 1 s post-perturbation according to EMG measurements (Shahvarpour et al., 2014).

For the current stability analyses, muscle stiffness, K_i, was evaluated at each time instance by $K_i = q(F_i/L_i)$ (Bergmark, 1989) in which F_i and L_i are instantaneous force and total length of muscle i respectively. Muscle stiffness coefficient, q, was considered constant for all muscles. In the current stability phase of analyses, every muscle i was substituted with a spring with an stiffness K_i evaluated at each time step as a function of its force and length taken based on earlier equilibrium phase of analyses (Shahvarpour et al., 2015). Using linear modal vibration approach, the stability analyses determined the smallest (undamped) natural frequency of the system at all times and deformed configurations as a function of q. The critical stiffness coefficient, q_{cr}, was subsequently sought as this fundamental natural frequency approached zero. A lower q_{cr} at a time instance indicates a higher margin of stability for the entire system so that at the limit when q_{cr} reaches zero, the trunk does not require any stiffness contribution any more from muscles in order to maintain stability. An iterative procedure was exploited to calculate q_{cr} at each time instance. Analyses were performed by ABAQUS/Standard 6.10-1 (Simulia Corp., Providence, RI).

Temporal variation of q_{cr} showed small fluctuations before the perturbation but a sudden drop after the perturbation. Consequently, the average q_{cr} values were evaluated over four separate time intervals: (1) pre-q over 256 ms before perturbation, (2) post-q1 over 60 ms post-perturbation set as the average reflex latency according to our earlier study (Shahvarpour et al., 2014), (3) post-q2 during 60–240 ms post-perturbation in which the reflex response translates into mechanical action (Shahvarpour et al., 2015) and finally (4) post-q3 from 240 ms to 1 s post-perturbation when the neural action was mostly voluntary.

Table 1
Parameters defining the six experimental conditions.

Condition	Preload (N)	Sudden load (N)	Initial posture	EO preactivation
C1	5	50	Upright	–
C2	5	100	Upright	–
C3	50	50	Upright	–
C4	50	100	Upright	–
C5	5	50	10 cm Anterior translation[a]	–
C6	5	100	Upright	10%

[a] The anterior translation was measured from the initial upright trunk position.

2.1. Statistical analyses

The evaluated variables were statistically analyzed using NCSS software (NCSS 8. NCSS, LLC. Kaysville, Utah, USA. www.ncss.com), using a significance level (alpha) of 0.05. One- and two-way analyses of variance (ANOVA), involving one (initial trunk flexion or EO antagonistic preactivation) or two (preload and sudden load) within-factors, were performed to evaluate the effect of preload (C1-2 vs C3-4), sudden load (C1 and C3 vs C2 and C4), trunk flexion (C1 and C3 vs C5) and abdominal preactivation (C2 and C4 vs C6) on trunk stability. These were repeated at each time interval (pre-q and post-q1–post-q3).

3. Results

The temporal variation of q_{cr} was calculated for 12 subjects and six experimental conditions (see Fig. 1 for subject 2). Statistical results revealed that the preload and sudden load did not have any interaction effect on q_{cr}, for any time interval (Table 2). Preload significantly increased Pre-q though sudden load did not influence this variable (Table 2 and Fig. 2). Post-perturbation variables were not affected by preload. However, while only a trend was observed in post-q1 ($p=0.082$), post-q2 ($p=0.004$) and post-q3 ($p<0.001$) significantly dropped with greater sudden load (Fig. 2).

Initial trunk flexion (C5) significantly decreased the q_{cr} pre-perturbation (pre-q) when compared to C1 (5-N preload) and C3 (50-N preload) (Table 2 and Fig. 3). Despite identical sudden load of 50 N, all post-perturbation stability variables were also significantly smaller in C5 than in C1 and C3.

Preactivation of abdominal muscles significantly decreased q_{cr} pre-perturbation (pre-q) with respect to C2 (5-N preload) and C4 (50-N preload) (Table 2 and Fig. 4). Post-q1 and post-q2 in C6 demonstrated a significant decrease vs C2 but not C4, although trends ($0.05<p<0.1$) were observed.

4. Discussion

The critical muscle stiffness coefficient, q_{cr}, modulates the stiffness of muscles and as such can be employed as a surrogate measure of the trunk stability margin. The stability margin at a loaded configuration denotes the residual load-carrying capacity of the system that can be resisted above and beyond the existing load before becoming unstable. Due to the crucial role of muscles in pre- and post-perturbation periods, this coefficient was chosen similar to our earlier studies (Bazrgari et al., 2008, 2009). For a given set of muscle forces, the trunk stability margin grows as q_{cr} drops so that at the limit when $q_{cr}=0$, the trunk requires no passive and active stiffness contributions from muscles in order to maintain stability although it continues to depend on muscle forces (but not muscle stiffnesses) for equilibrium and stability. This coefficient was calculated at all times pre- and post-perturbations and for all conditions (Table 1). The results demonstrated that higher preload significantly reduced the pre-perturbation q_{cr} indicating the effect of larger muscle forces and hence muscle stiffnesses in increasing trunk stability. Higher amplitude of sudden load significantly increased stability (i.e. smaller q_{cr}) post-perturbation (due to larger muscle forces/stiffness and greater passive stiffness at larger flexion) especially after the back muscles reflex onset. Trunk stability was also substantially improved throughout when the trunk